Report No. CG-D-7-85

U.S. COAST GUARD PATROL BOAT (WPB)
HYDROFOIL FEASIBILITY DESIGN

DECEMBER 1984

FINAL REPORT

Prepared for:

U.S. Department of Transportation
United States Coast Guard
Office of Research and Development
Washington, D.C. 20593

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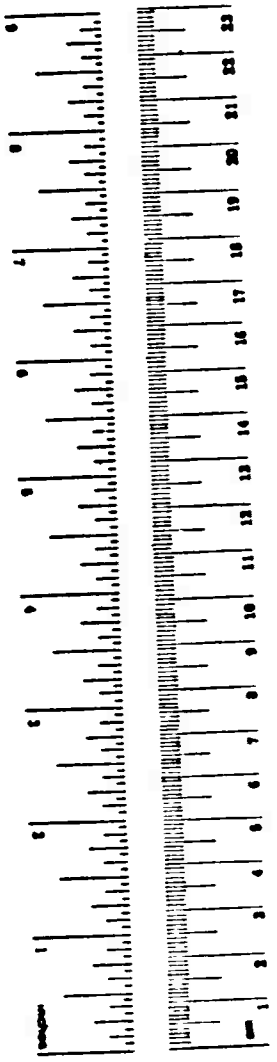
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

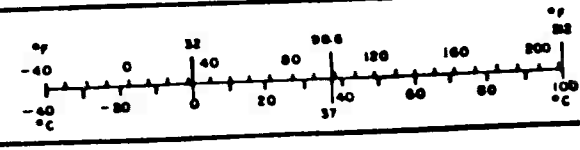
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

A WPB HYDROFOIL (WPB-H) FEASIBILITY DESIGN TO MEET SPECIFIC U. S. COAST GUARD REQUIREMENTS WAS DEVELOPED. THIS REPORT CONTAINS THE TECHNICAL DETAILS AND CONCEPTUAL DRAWINGS OF THE WPB-H DESIGN. INCLUDED ARE A DESCRIPTION OF THE PHYSICAL CHARACTERISTICS WITH A WEIGHT BREAKDOWN, IN ADDITION TO ENGINEERING AND OPERATIONAL CHARACTERISTICS. THIS BASELINE, 35 KNOT FULLY SUBMERGED HYDROFOIL AT A FULL LOAD WEIGHT OF 137 LTONS, SATISFIES THE 5-DAY USCG MISSION REQUIREMENT AT A 30 KNOT FOILBORNE CRUISE SPEED AND A 12 KNOT HULLBORNE SPEED. THE SHIP'S CREW OF 16 CONSISTS OF 2 OFFICERS, 2 CPOS AND 12 ENLISTED. THE WPB-H PAYLOAD OF 12.5 LTONS INCLUDES 2.5 LTONS OF ARMAMENT.

TWO VARIANTS WERE INVESTIGATED TO DETERMINE THE IMPACT OF INCREASING AND DECREASING DESIGN SPEED BY 5 KNOTS. IT WAS CONCLUDED THAT THE 30 KNOT DESIGN DOES NOT OFFER ANY SIGNIFICANT ADVANTAGES OVER THE 35 AND 40 KNOT DESIGNS. THE HIGHER SPEED VARIANT PROVIDES A 5 KNOT GREATER SPEED THAN THE BASELINE WITH NO TECHNICAL PENALTIES.

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POWER	WEIGHTS	
RANGE		
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ABSTRACT

A WPB hydrofoil (WPB-H) feasibility design to meet specific U.S. Coast Guard requirements was developed. This report contains the technical details and conceptual drawings of the WPB-H design. Included are a description of the physical characteristics with a weight breakdown, in addition to engineering and operational characteristics. This baseline, 35-knot fully submerged hydrofoil at a full load weight of 137 L.tons satisfies the 5-day USCG mission requirement at a 30-knot foilborne cruise speed and a 12 knot hullborne speed. The ship's crew of 16 consists of 2 officers, 2 CPOs and 12 enlisted. The WPB-H payload of 12.5 L.tons includes 2.5 L.tons of armament.

Two variants were investigated to determine the impact of increasing and decreasing design speed by 5 knots. It was concluded that the 30 knot design does not offer any significant advantages over the 35 and 40 knot designs. The higher speed variant provides a 5 knot greater speed than the baseline with no technical penalties.

Keywords: Patrol boat, Range, Motions Stability, Feasibility design + weights.

ADMINSTRATIVE INFORMATION

The WPB hydrofoil feasibility design described in this report was developed for the United States Coast Guard (MIPR DTCG 23-84-F-20048, Work Unit 1-1153-403) by the David Taylor Naval Ship R&D Center. The purpose of the study is to provide hydrofoil design information which satisfies the requirements stated by the USCG in the MIPR. The USCG sponsor is LCDR Peter Boyd.

INTRODUCTION

A series of conceptual hydrofoil designs were previously explored for the U.S. Coast Guard and reported in reference 1. The concepts included fully submerged foil and surface-piercing foil designs over a displacement range of 100 to 400 tons. They satisfied requirements for the postulated missions of three U.S. Coast Guard ship types: Patrol Boat (WPH), Patrol Cutter (WPC) and Patrol Corvette (WKE). It should be noted that both diesel and gas turbine powerplants were examined for the foilborne propulsion systems of all ship types.

As a result of a review of the above conceptual designs and an examination of the most recent WPB replacement requirements promulgated by the USCG in Table 1, it became evident that the 141 L.ton hydrofoil with fully submerged foils and gas turbine foilborne propulsion (WPC(H)) should be used as the baseline for the current study. This report contains the technical details and conceptual drawings of the WPB-H design (a variation of WPC(H)) which meets the requirements stated in Table 1. Included in the report is a description of the physical characteristics with a weight breakdown, engineering characteristics and operational characteristics. The latter covers range/endurance, speed (and speed degradation), projected motions, towing and boat launch and retrieval. In addition, two variants of the design are examined: one at a design speed of 5 knots less and another at 5 knots greater, than the baseline design speed of 35 knots.

In all of these hydrofoil designs an interactive computer program, Hydrofoil Analysis and Design (HANDE), reference 2, was used. HANDE is a well established program developed by the U.S. Navy as an aid in the design of fully submerged hydrofoils.

PHYSICAL CHARACTERISTICS

GENERAL DESCRIPTION

The WPB hydrofoil (WPB-H) described in this report is based upon a 141 L.ton design with fully submerged foils developed in reference 1. Several changes in the hull were made to improve the layout and damage stability characteristics. These included shortening the hull, adding a watertight bulkhead at station 8.9 and moving the two forward watertight bulkheads forward.

TABLE 1 - WPB REQUIREMENTS

1) Endurance - Approximately 5 days endurance is required. The crew, fuel and payload associated with 5 days endurance are addressed separately below.

2) Speed - A propulsion system is desired that will provide both hot pursuit speed and fuel economy when patrolling. An economical patrol speed around 10 kts with a maximum continuous speed greater than 20 kts are considered minimum requirements.

3) Range - A minimum range of 1440 nm is desired based on the following combination:

10 kts (minimum) for 96 hrs
20 kts (minimum) for 24 hrs

4) Seakeeping - Minimal motion underway and DIW are important to reducing crew fatigue and improving operations (boat launch/recovery, surveillance, navigation, etc.). Proven systems for reducing motions are desired.

5) Crew - The mission of the WPB in combination with the size of the WPB dictate a crew of 16 as follows:

2	Officers
2	CPO's
12	Enlisted
16	TOTAL

In addition two (2) spare bunks shall be provided.

6) Payload

Crew & Effects	3.0 L.tons
Provisions	2.5 L.tons
Water	4.5 L.tons
TOTAL	10.0 L.tons

7) Boat/Launch/Retrieval Capability - 5.4M RHI with 70 hp O/B and powered davit. Two-sided capability preferred.

8) Towing - Towing bitt and towing arrangement adequate to tow 500 L.ton vessel.

9) Armament - (1) 25mm with 2000 rounds
(2) 50 caliber MG's with 4000 rounds.

10) Damage Control - 2 compartment damage stability.

11) Miscellaneous - Anchoring and refueling at-sea capability must be provided.

Changes were also made to the strut/foil system to improve performance in the 30-knot regime.

Key characteristics of the WPB-H are given in Table 2. Depicted here are major dimensions, weights, speed, range, endurance, propulsion items and foil/strut information. The ship is illustrated in Figures 1, 2 and 3 in terms of outboard profile, inboard profile and deck plans.

The WPB-H is powered in the foilborne mode by a single LM-500 gas turbine driving through a splitter gear box and two Zee-drives to propellers mounted on pods at the bases of the aft struts. In the hullborne case, a Detroit Diesel engine provides power to a single propeller outdrive via an in-line drive shaft. Two 140-kW, diesel-driven, electric generators provide 60 Hz electrical power. The ship's electrical systems are conventional; however, details of the systems have not been determined.

The foil system is a canard type with approximately 35% of the load on the forward T-foil. The WPB-H forward foil has a foil loading of 996 psf, while the aft Pi-type foil loading is 1000 psf. The foil-strut system is retractable to minimize draft for hullborne operations in shallow coastal water and harbors.

It is possible for the WPB-H to operate hullborne with the foilborne propulsion system. The foilborne system can be used with one or two propellers, but the more highly loaded single screw operates somewhat more efficiently, and thus would provide greater hullborne range.

TABLE 2 - WPB HYDROFOIL PHYSICAL CHARACTERISTICS

SIZE:	
LOA	108 feet
LBP	105 feet
Hull Material	Welded Aluminum
Beam (at deck)	28.4 feet
Beam (at waterline)	21.1 feet
Max Span (over foils)	38.27 feet
Draft (HB, foils down)	15.2 feet
Draft (HB, foils up)	4.4 feet
Depth at midships	11.93 feet
Hull Volume	21,589 cubic feet
Deck House Volume	6,312 cubic feet
Total Volume	27,901 cubic feet
Lightship Weight	97.2 Tons
Full Load Weight	137.0 Tons
SPEED:	
Foilborne Design	35 knots
Takeoff	22 knots
Hullborne Design	12 knots
RANGE:	
Foilborne at 30 kts	1,165 nm
Hullborne at 12 kts	3,113 nm
ENDURANCE:	
Five-Day Mission	12 knots for 96 hours, and 30 knots for 24 hours, for total of 120 hours and 1872 nm
PROPULSION:	
Foilborne	(1) LM-500; (2) Zee-drives
Hullborne	(1) Decroit Diesel 12V-71TI(L)
Electric Prime Mover	Diesel, 280 kw
Foilborne hp Required	3,500 hp at 35 kts
Takeoff hp Required	3,784 hp
Takeoff Thrust Margin	30%
Hullborne hp Required	627 hp at 12 kts
FOILS:	
Foil Concept	Canard (T/Pi) 35% fwd, 65% aft
Strut/Foil Material	Struts: HY-130 Foils: HY-130

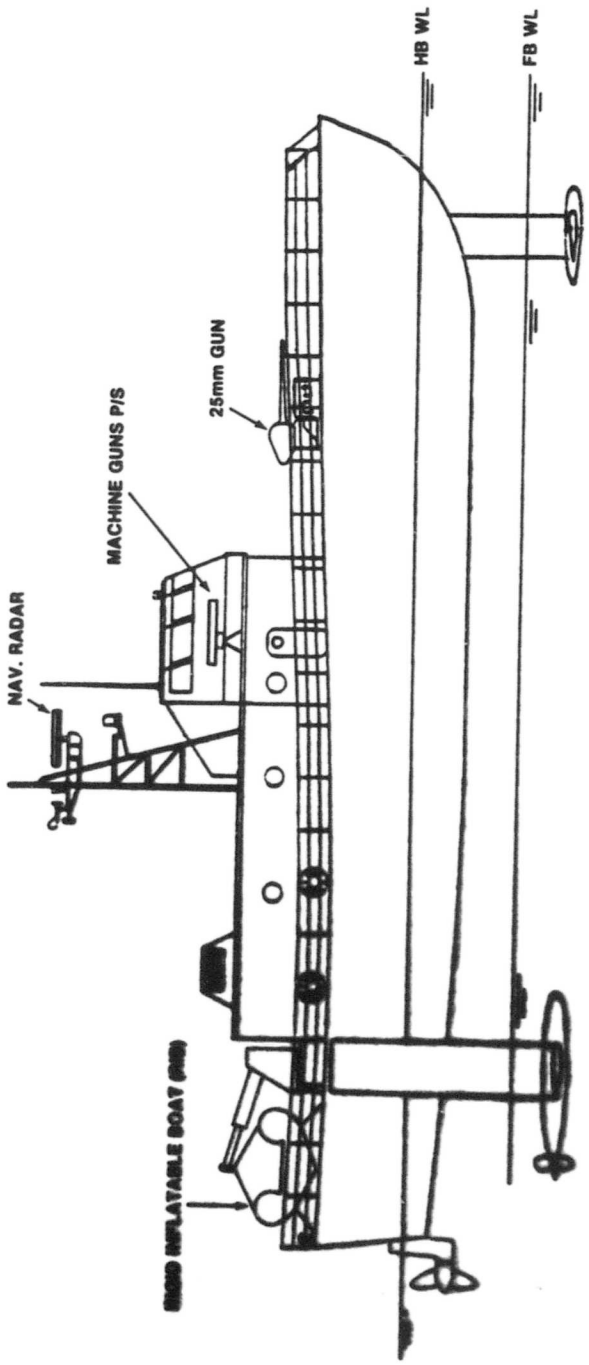


Figure 1 - WPB-H Outboard Profile

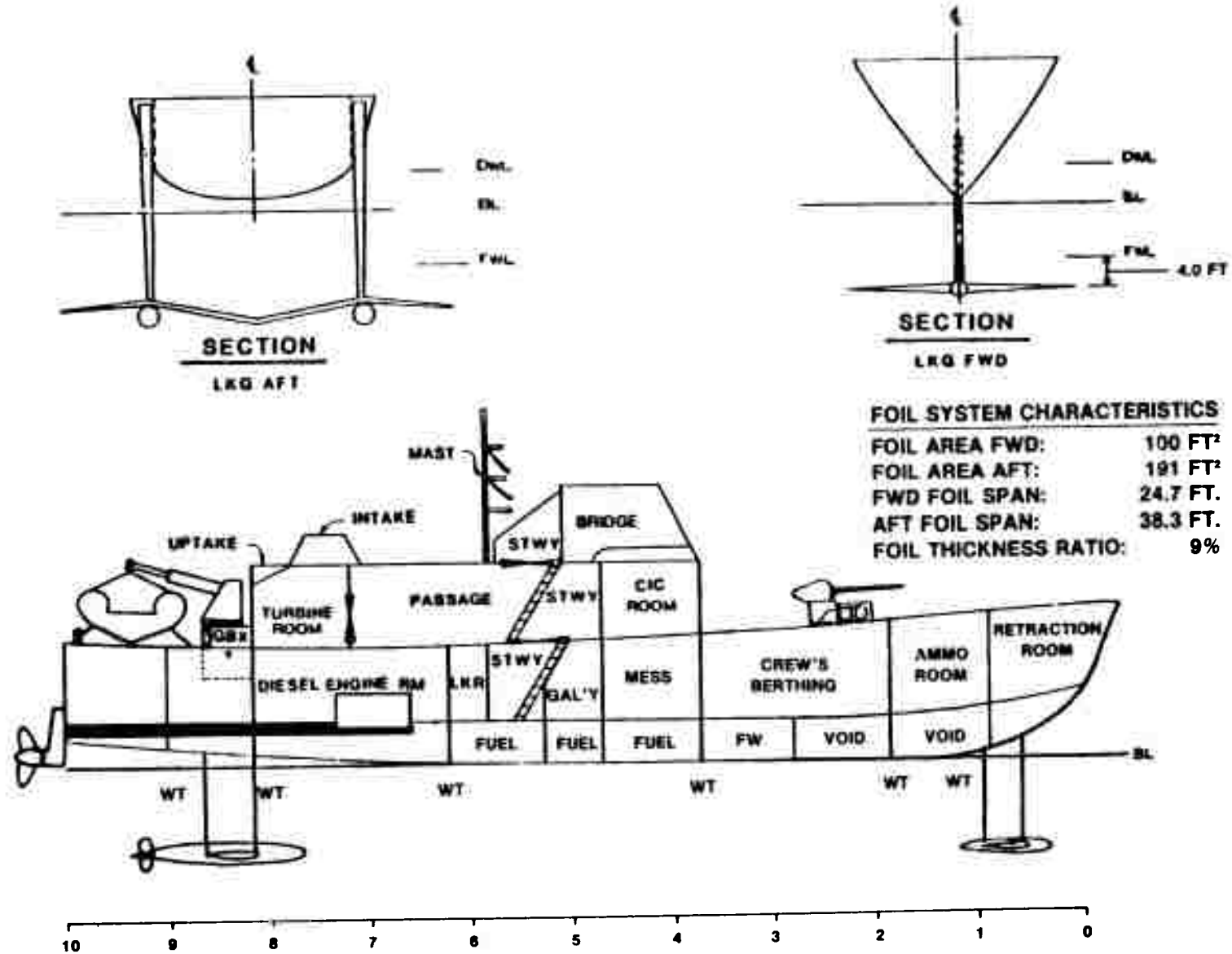


Figure 2 - WPB-H Inboard Profile

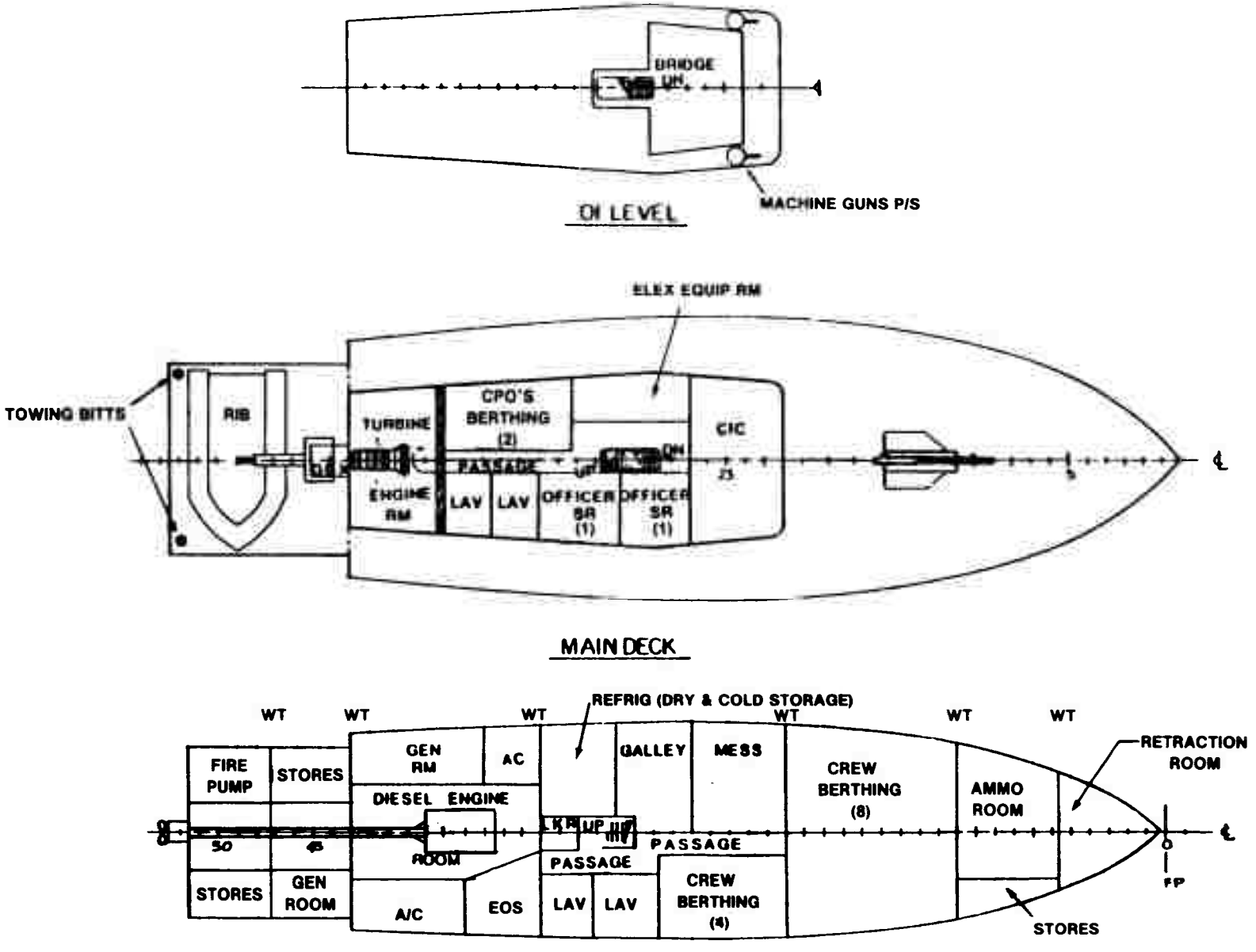


Figure 3 - WPB-H Deck Plans

WEIGHT BREAKDOWN

The WPB-H weight breakdown as shown in Table 3 was derived from HANDE with certain exceptions. The USCG directed that SWBS Group 400, Command and Surveillance be standardized at 2.0 L.tons. Also SWBS Group 700 (Armament) was standardized at 2.5 tons which included 2000 rounds of 25mm and 4000 rounds of 50 caliber ammunition. Additionally, potable water was set at 4.5 L.tons, crew and effects at 3.0 L.tons, and stores at 2.5 L.tons. Total useful payload is therefore 12.5 L.tons (including armament).

The WPB-H lightship weight is about 97 tons which includes a 10% margin (as required by USCG). Full load weight is 137 L.tons with a dynamic lift of 30 L.tons and foilborne foil/strut buoyancy of 7 L. tons. Two tons has been included in SWBS Group 500 to provide for a light-weight crane and a small rigid hull inflatible (RHI) boat.

TABLE 3 - WPB HYDROFOIL WEIGHT BREAKDOWN

SWBS	Group		Weight (L.tons)
100	Hull Structure		28.4
200	Propulsion Plant		12.5
	FB Components	6.0	
	HB Components	6.5	
300	Electric Plant		10.6
400	Command & Surveillance		2.0
500	Auxiliary Systems		22.1
	Systems (less 567)	12.2	
	F/S Assemblies	9.9	
600	Outfit & Furnishings		10.4
700	Armament		2.5
M00	Margins (10%)		8.7
	LIGHTSHIP		97.2
F00	Full Loads		39.8
F10	Crew & Effects	3.0	
F30	Provisions	2.5	
F42	Fuel (98% usable)	29.5	
F46	Lube Oil	0.3	
F50	Fresh Water	4.5	
	FULL LOAD WT-FOILS DOWN		137.0
	FB Foil/Strut Buoyancy		-7.0
	FULL LOAD DYNAMIC LIFT		130.0

ENGINEERING CHARACTERISTICS

HULL

Hull lines were developed using HIGHPOINT (PCH-1) as a baseline. This hull form has a shallow deadrise of 8.5 degrees and rounded chine. As a result of several iterations of the design to meet the payload, space and mission requirements, the final hull length between perpendiculars is 105 feet and waterline beam is 21.1 feet with a maximum beam at the deck of 28.4 feet.

The hull has 6 watertight bulkheads which are sufficient to satisfy damaged stability as discussed in more detail in a later section.

Hull structural design is an output of HANDE. It was based on a selection of 5086 aluminum for the hull and superstructure.

DRAG AND POWERING

Drag and powering predictions are made using HANDE for both the hullborne and foilborne modes. Drag vs speed for the WPB-H design described in this report is shown in Figure 4. Both hullborne drag and foilborne drag curves are shown for full load and range load (1/2 fuel burned off) conditions of 137 tons and 120, tons respectively.

Powering predictions are shown in Figure 5. During the iteration of the design, several variations in forward and aft foil loadings were made to produce a minimum power requirement between 25 and 30 knots, a takeoff margin of 25% or greater, and at the same time provide a maximum speed of at least 35 knots. Foilborne propeller design was also modified from the original WPC(H) design to satisfy these requirements. The foilborne power curves for full load and half-fuel load conditions are shown in Figure 5 along with the full load hullborne power curve in the lower speed regime. The HANDE takeoff analysis predicts a takeoff speed of 22 knots. Note that from the shape of the foilborne power curves, a minimum "flying" speed is predicted to be about 24 to 26 knots depending upon fuel remaining.

PROPULSION

From analyses made in reference 1, it was concluded that for this size hydrofoil, a gas turbine is preferred to a high speed diesel engine. The General Electric LM-500 gas turbine (or equivalent) rated at 4000 hp (max continuous) is an acceptable existing gas turbine which satisfies the maximum

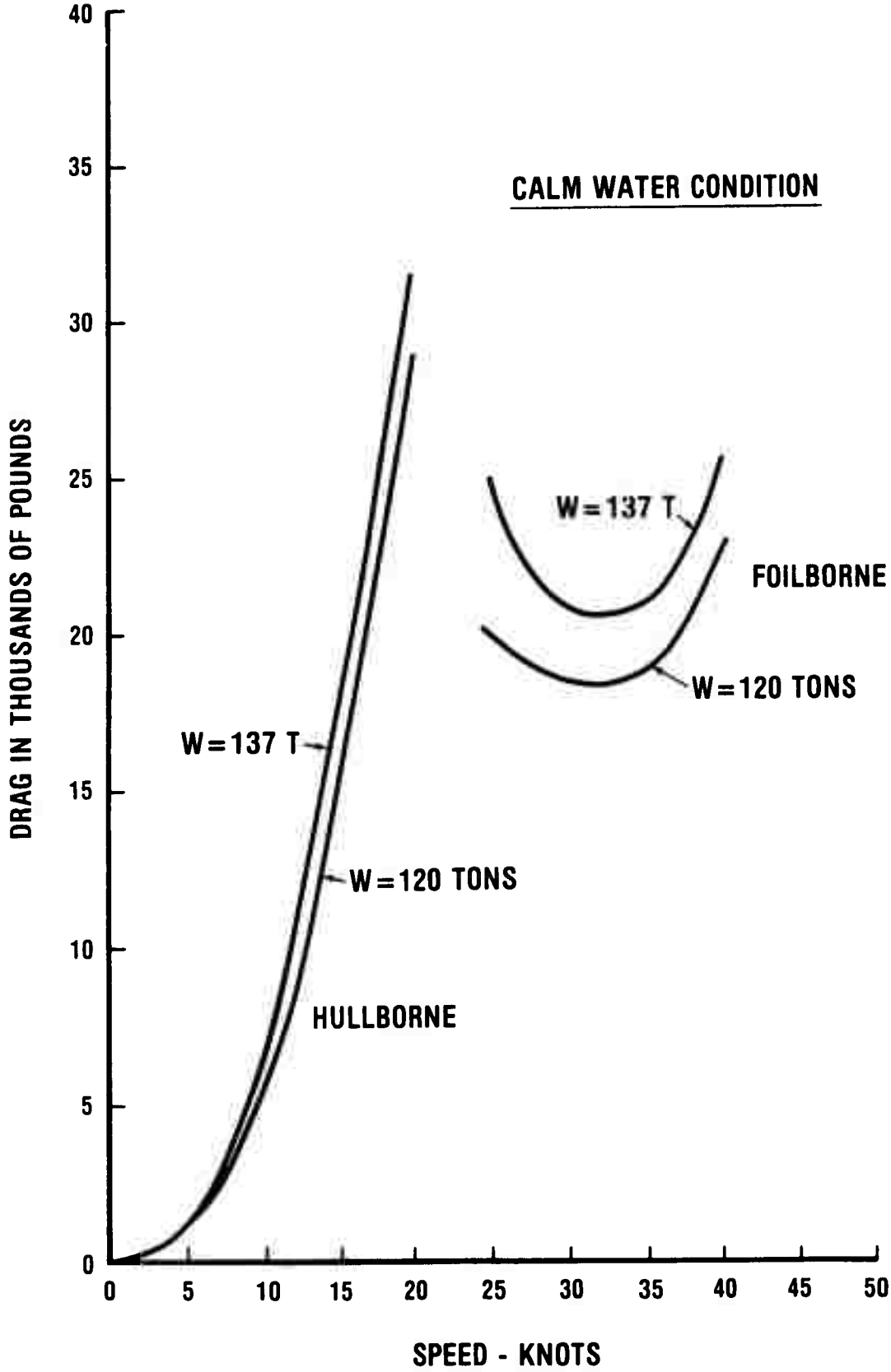


Figure 4 - WPB-H Drag vs Speed

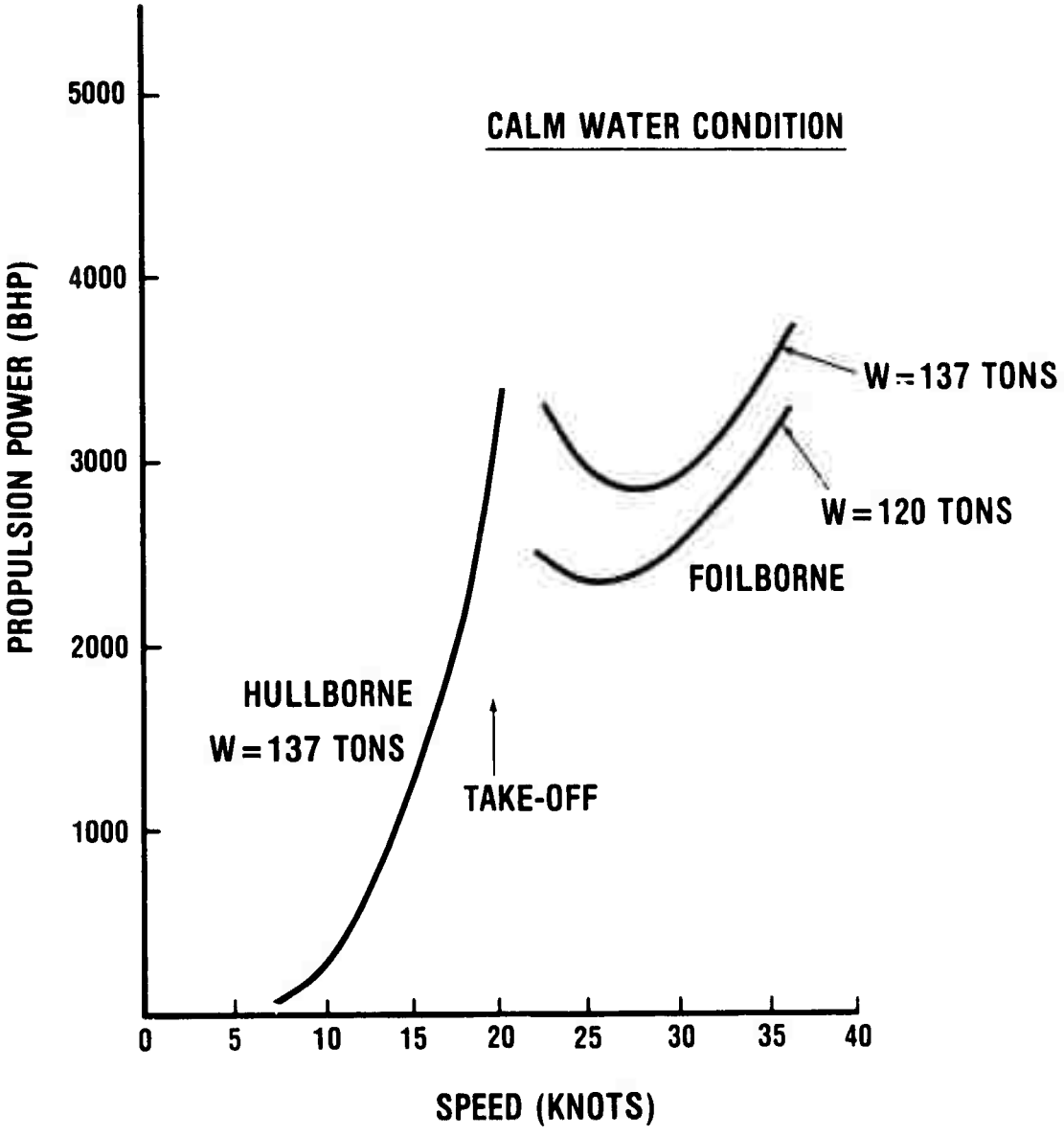


Figure 5 - WPB-H Power Required

continuous power requirement of about 3500 hp at 35 knots under the full load condition. See Figure 6 for LM-500 specific fuel consumption (SFC) and power characteristics.

The single LM-500 engine is derated to 3500 bhp. It drives into a splitter gear box, through two lateral shafts to a bevel gear box at the top of each aft strut. A single shaft in each strut drives into a similar bevel gear box and planetary box within each propulsion pod. One fixed pitch propeller 3.7 ft in diameter is driven at the aft end of each propulsion pod.

Foilborne propulsion system characteristics are shown in Figures 6 through 9 and include specific fuel consumption, propulsive efficiency, fuel flow (L.tons per hour) and fuel consumption (nm per L.ton) plotted against speed.

The hullborne propulsion system is independent of the foilborne system. It consists of a Detroit Diesel 12V-71TI diesel engine rated at 650 hp maximum continous at 2300 rpm. It drives thru a coupling and clutch via a horizontal shaft to the transom. Here a stern drive is incorporated with a vertical and horizontal rotatable feature, similar to that on the HIGH POINT (PCH-1). This allows the propeller to be rotated up behind the stern during foilborne operations. Also the 360° rotation about a vertical axis provides an excellent low speed maneuvering and docking capability. The hullborne fuel flow characteristics for both the hullborne and foilborne propulsion systems in calm water are shown in Figure 8b. The diesel engine characteristics in terms of specific fuel consumption and power are shown in Figure 10.

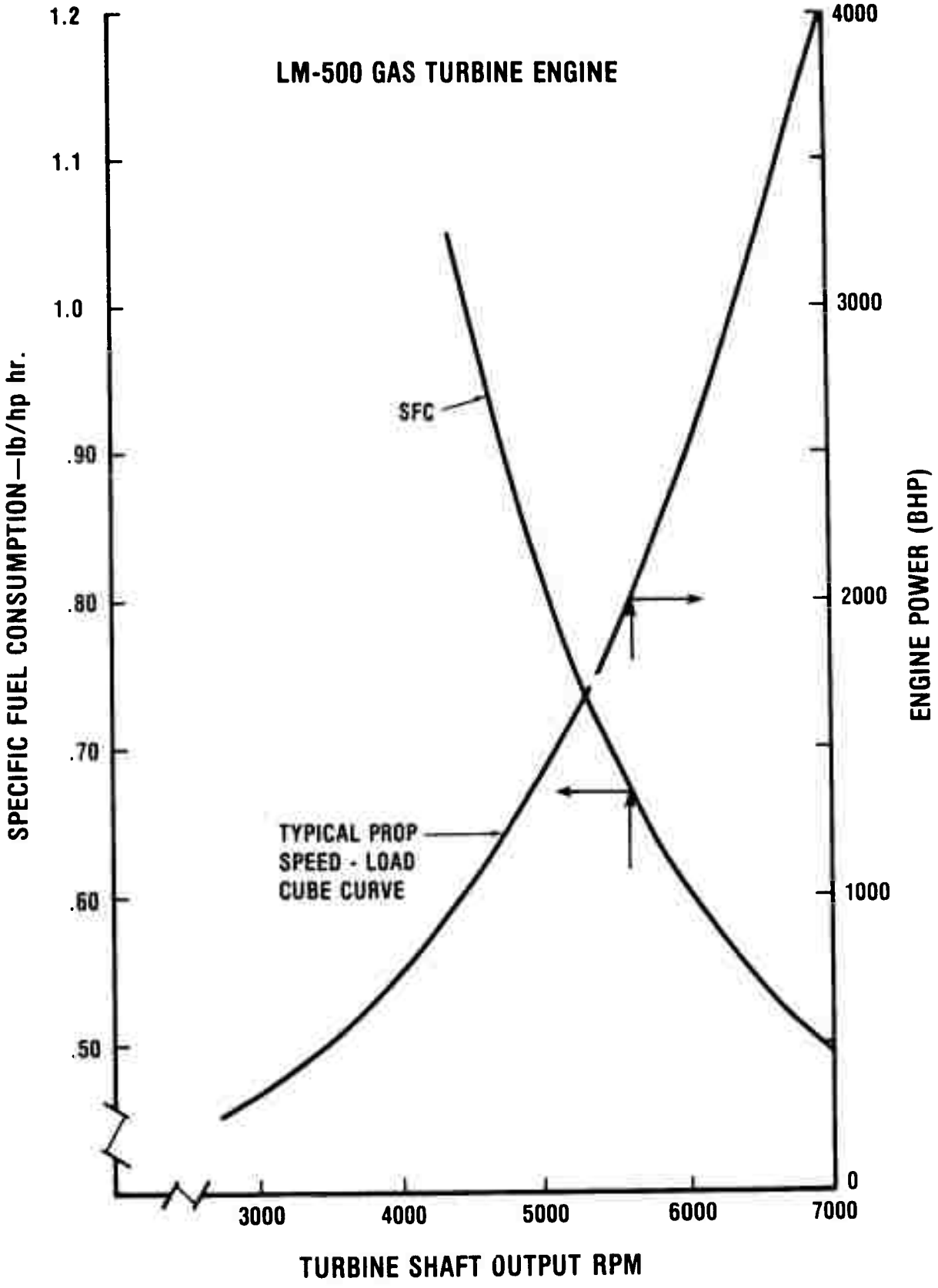


Figure 6 - WPB-H Foilborne Power Plant Characteristics

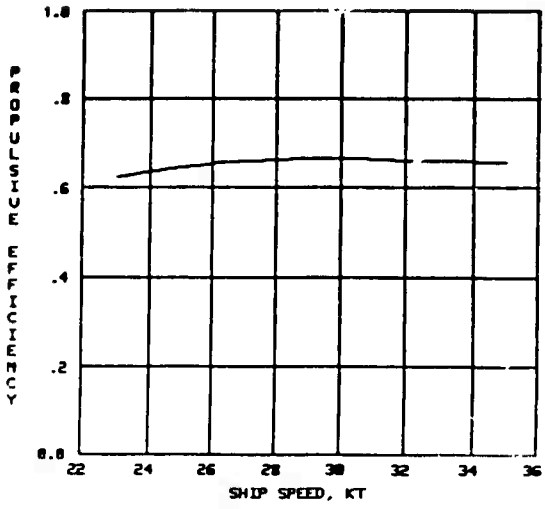


Figure 7. WPB-H FOILBORNE PROPULSIVE EFFICIENCY

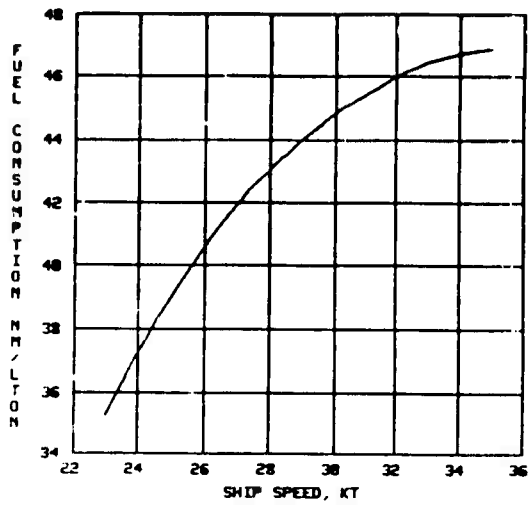


Figure 9. WPB-P FOILBORNE FUEL CONSUMPTION

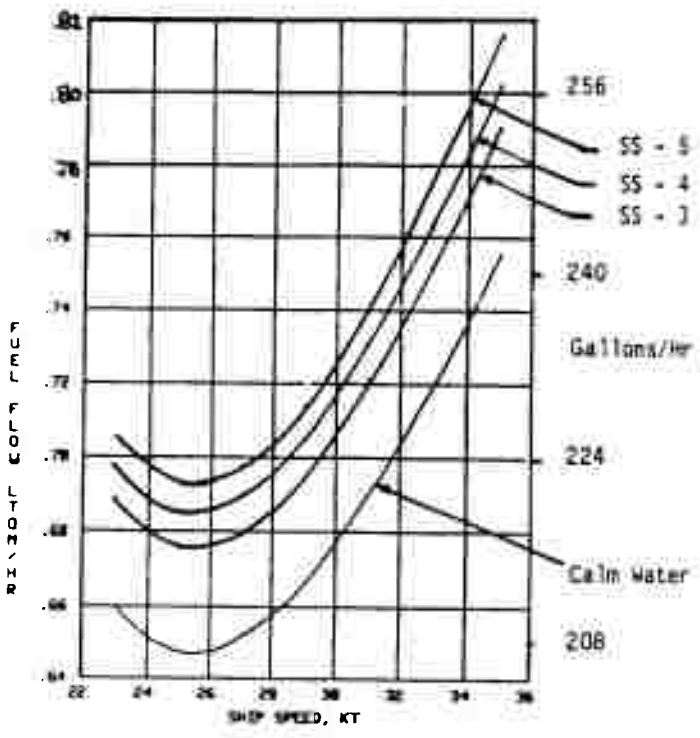


Figure 8. WPB-H FOILBORNE FUEL FLOW

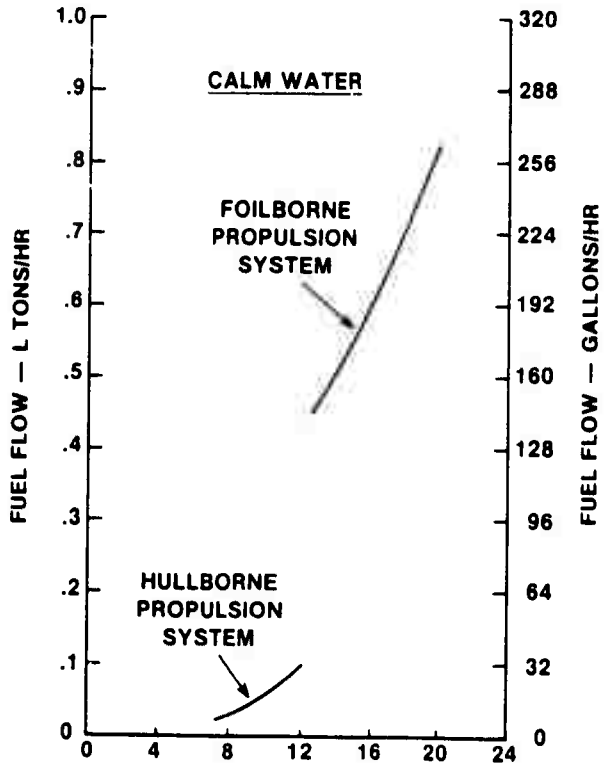
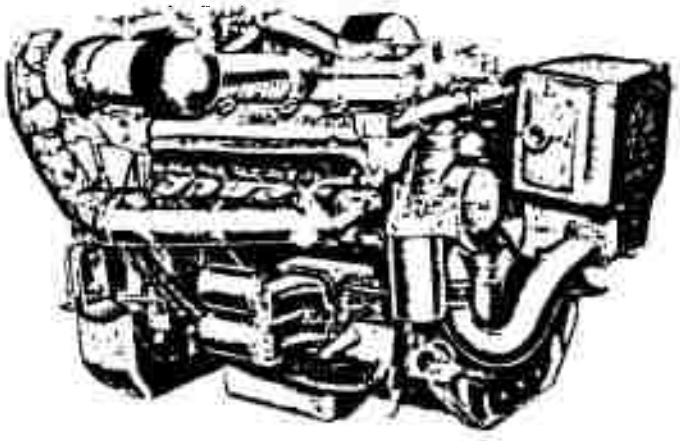


Figure 8b. WPB-H HULLBORNE FUEL FLOW

Detroit - Diesel Marine Models 12V-71TI



Typical Low Profile 12V-71TI Marine Model

RATING EXPLANATION

RATED BHP—Basic engine gross power.

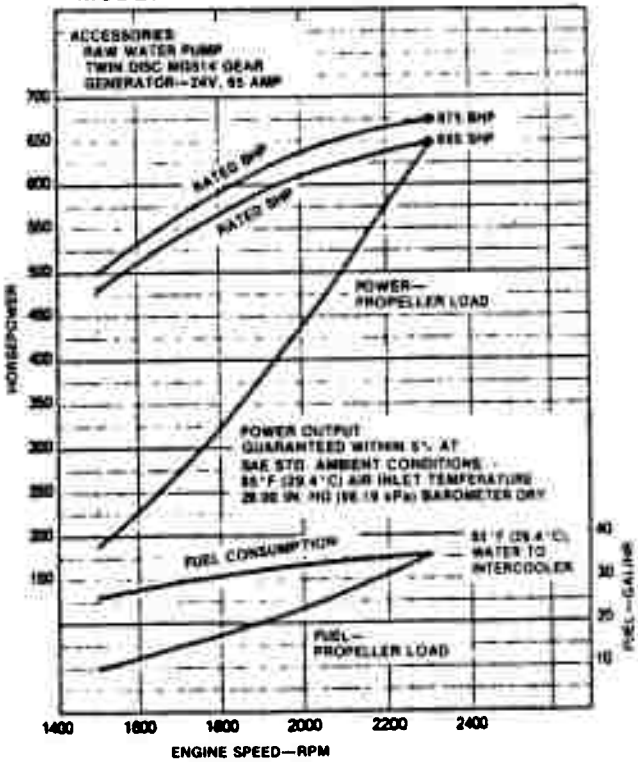
RATED SHP—Net power available at the marine gear output shaft; this rating is recommended for pleasure craft applications.

PROPELLER LOAD—Indicates horsepower absorbed by a typical propeller and the corresponding fuel consumption throughout the speed range.

SPECIFICATIONS

Basic Engine	12V-71TI Low Profile
Model	
Port	7122-3301
Starboard	7122-7301
Number of Cylinders	12
Bore and Stroke	4.25 in. x 5 in. (108 mm x 127 mm)
Two Cycle Displacement	852 cu. in. (13.96 litres)
Rated Gross Power: 60°F (15.6°C) and Sea Level	—
SAE: 85°F (29.4°C) and 500 ft. (152.4 m)	675 BHP (504 kW) @ 2300 RPM
Rated Net Power: SAE: 85°F (29.4°C) and 500 ft. (152.4 m)	650 SHP (485 kW) @ 2300 RPM
Compression Ratio	17 to 1
Net Weight (Mass) (dry) (approx.)	5200 lbs. (2359 kg)

ENGINE PERFORMANCE
MODEL 12V-71TI WITH N90 INJECTORS



kW as shown is the metric equivalent power to horsepower rating.

Figure 10 - Hullborne Power Plant Characteristics

STABILITY

Intact and damaged stability calculations were made using the HANDE program. A summary of the factors related to the hydrostatic analysis is shown in Table 4 for the full load and minimum operation conditions. The weight corresponding to the minimum operating condition (namely 100 L.tons) was calculated on the basis of 37 tons of fuel, stores and water being consumed during the voyage.

Tables 5 and 6 shown the intact and damaged stability characteristics for the WPB hydrofoil design for both full load and minimum operating conditions.

Plots of WPB-H intact stability characteristics (from Table 5) for full load and minimum operating conditions (with foils down) are shown in Figures 11-a and 11-b. Clearly, for a 70-knot wind speed the intact stability criteria are satified under both conditions.

TABLE 4 - WPB-H HYDROSTATIC ANALYSIS SUMMARY

FULL LOAD CONDITION

HYDROSTATIC IND-H WT
FOIL POS IND-DOWN

DISPLACEMENT, LTON	136.90	LCG LOC(+VE FWD MID), FT	-2.63
MIDSHIP DRAFT, FT	4.38	TRIM(+ BY STERN), FT	0.00
SHIP KG, FT	7.38	LEAST LIMITING KG, FT	9.70
MAX AREA STA LOC FM FP,FT	50.28	AREA AT MAX AREA STA, FT2	69.599
BEAM AT MAX AREA STA, FT	21.59	BLOCK COEFFICIENT	.449
PRISMATIC COEFFICIENT	.609	SECTIONAL AREA COEF	.736
METACENTRIC HT(GM), FT	6.01	SHIP LBP, FT	105.00

MINIMUM OPERATING CONDITION

DISPLACEMENT, LTON	100.00	LCG LOC(+VE FWD MID), FT	-1.27
MIDSHIP DRAFT, FT	3.62	TRIM(+ BY STERN), FT	0.00
SHIP KG, FT	8.06	LEAST LIMITING KG, FT	8.95
MAX AREA STA LOC FM FP,FT	49.98	AREA AT MAX AREA STA, FT2	53.758
BEAM AT MAX AREA STA, FT	20.43	BLOCK COEFFICIENT	.407
PRISMATIC COEFFICIENT	.561	SECTIONAL AREA COEF	.726
METACENTRIC HT(GM), FT	5.90	SHIP LBP, FT	105.00

TABLE 5 - WPB-H INTACT STATIC STABILITY

FULL LOAD CONDITION

LAT RESIST CENTER, FT	8.12	INTACT WIND SPEED, KT	70.00
SAIL AREA, FT2	1616.25	SAIL AREA FACTOR	1.25
WIND LEVER ARM, FT	1.01	WIND LIMITING KG, FT	9.70
TURN SPEED, VK	12.00	TURN RADIUS, FT	236.00
TURN LEVER ARM, FT/FT	.05	TURN LIMITING KG, FT	10.00

TABLE OF INTACT RIGHTING ARMS(RA), DRAFTS, AND TRIMS

HEEL, DEG	0.00	5.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00
RA, FT	0.00	.51	.98	1.79	2.40	2.91	3.25	2.67	2.21	1.36
TRIM, FT	0.00	-.01	-.04	-.25	-.61	-1.05	-1.51	-2.75	-4.58	-9.31
DRAFT, FT	4.38	4.35	4.28	3.93	3.21	1.97	.19	-2.66	-8.22	-24.39

MINIMUM OPERATING CONDITION

LAT RESIST CENTER, FT	7.74	INTACT WIND SPEED, KT	70.00
SAIL AREA, FT2	1714.86	SAIL AREA FACTOR	1.25
WIND LEVER ARM, FT	1.49	WIND LIMITING KG, FT	8.95
TURN SPEED, VK	12.00	TURN RADIUS, FT	236.00
TURN LEVER ARM, FT/FT	.05	TURN LIMITING KG, FT	9.89

TABLE OF INTACT RIGHTING ARMS(RA), DRAFTS, AND TRIMS

HEEL, DEG	0.00	5.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00
RA, FT	0.00	.49	.94	1.56	1.89	2.31	2.82	2.42	1.76	.86
TRIM, FT	0.00	-.06	-.23	-.68	-1.31	-2.03	-2.60	-3.83	-6.24	-12.42
DRAFT, FT	3.62	3.59	3.49	3.06	2.23	.84	-1.30	-4.83	-11.60	-31.55

TABLE 6 - WPB-H DAMAGED STATIC STABILITY
FULL LOAD CONDITION

LAT RESISTANCE CENTER, FT	8.12	DAMAGED WIND SPEED, KT	20.00
SAIL AREA, FT2	1616.25	SAIL AREA FACTOR	1.25
WIND LEVER ARM, FT	.06		

COMPARTMENT DESCRIPTIONS

COMP	SYMMETRY	PERM	FBHD,FT	ABHD,FT
1	C	.950	-1.23	9.54
2	C	.950	9.54	19.09
3	C	.950	19.09	38.18
4	C	.950	38.18	62.04
5	C	.950	62.04	82.10
6	C	.950	82.10	93.45
7	C	.950	93.45	105.00

TABLE OF DAMAGED RIGHTING ARMS(RA), DRAFTS, AND TRIMS, FT

HEEL, DEG		-15.0	-5.0	0.0	5.0	10.0	15.0	20.0	25.0	35.0	45.0
DAMAGED COMPTS											
RA	1 2	-1.47	-.53	0.00	.53	1.03	1.47	1.88	2.23	2.85	3.16
TRIM	1 2	-1.67	-1.48	-1.46	-1.48	-1.56	-1.67	-1.83	-2.00	-2.27	-2.66
DRAFT	1 2	4.41	4.64	4.66	4.64	4.56	4.41	4.20	3.89	2.88	1.38
RA	2 3	-1.37	-.48	0.00	.48	.94	1.37	1.78	2.17	2.59	2.63
TRIM	2 3	-7.45	-6.99	-6.94	-7.00	-7.19	-7.45	-7.81	-8.23	-9.61	-11.68
DRAFT	2 3	5.82	6.00	6.03	6.00	5.94	5.82	5.63	5.35	4.66	3.72
RA	3 4	-1.11	-.36	0.00	.38	.76	1.11	1.46	1.75	2.06	2.03
TRIM	3 4	-7.36	-7.27	-7.27	-7.27	-7.29	-7.36	-7.46	-7.68	-8.59	-10.17
DRAFT	3 4	7.57	7.71	7.73	7.71	7.67	7.57	7.43	7.26	6.82	6.28
RA	4 5	-.83	-.26	0.00	.26	.53	.83	1.15	1.49	1.99	2.03
TRIM	4 5	.65	.50	.48	.50	.55	.65	.78	.92	1.24	1.62
DRAFT	4 5	6.78	6.89	6.91	6.89	6.85	6.78	6.66	6.49	6.01	5.44
RA	5 6	-1.03	-.33	0.00	.33	.67	1.03	1.40	1.80	2.43	2.56
TRIM	5 6	4.47	4.25	4.23	4.25	4.33	4.46	4.65	4.87	5.47	6.76
DRAFT	5 6	5.41	5.56	5.58	5.56	5.51	5.41	5.26	5.04	4.34	3.39
RA	6 7	-1.19	-.39	0.00	.39	.79	1.19	1.59	2.00	2.67	2.83
TRIM	6 7	4.74	4.58	4.54	4.58	4.65	4.74	4.84	4.95	5.20	6.61
DRAFT	6 7	4.71	4.89	4.90	4.89	4.82	4.71	4.53	4.27	3.41	2.19

TABLE 7 - WPB-H DAMAGED STATIC STABILITY
MINIMUM OPERATING CONDITION

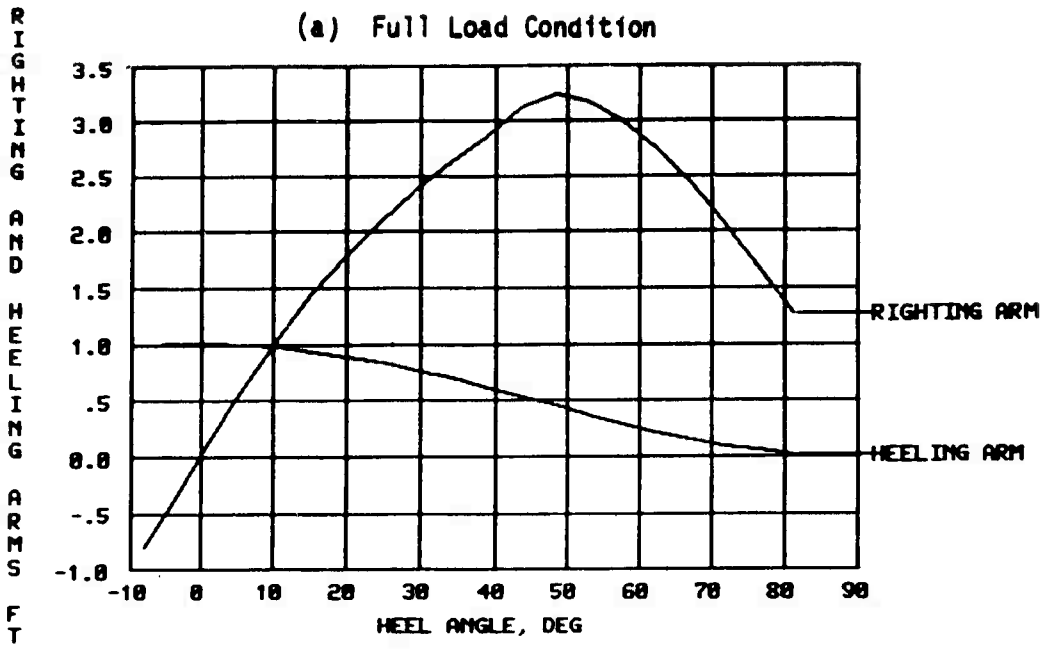
LAT RESISTANCE CENTER, FT	7.74	DAMAGED WIND SPEED, KT	20.00
SAIL AREA, FT2	1714.86	SAIL AREA FACTOR	1.25
WIND LEVER ARM, FT	.12		

COMPARTMENT DESCRIPTIONS

COMP	SYMMETRY	PERM	FBHD,FT	ABHD,FT
1	0	.950	-1.23	9.54
2	0	.950	9.54	19.09
3	0	.950	19.09	38.18
4	0	.950	38.18	62.04
5	0	.950	62.04	82.10
6	0	.950	82.10	93.45
7	0	.950	93.45	105.00

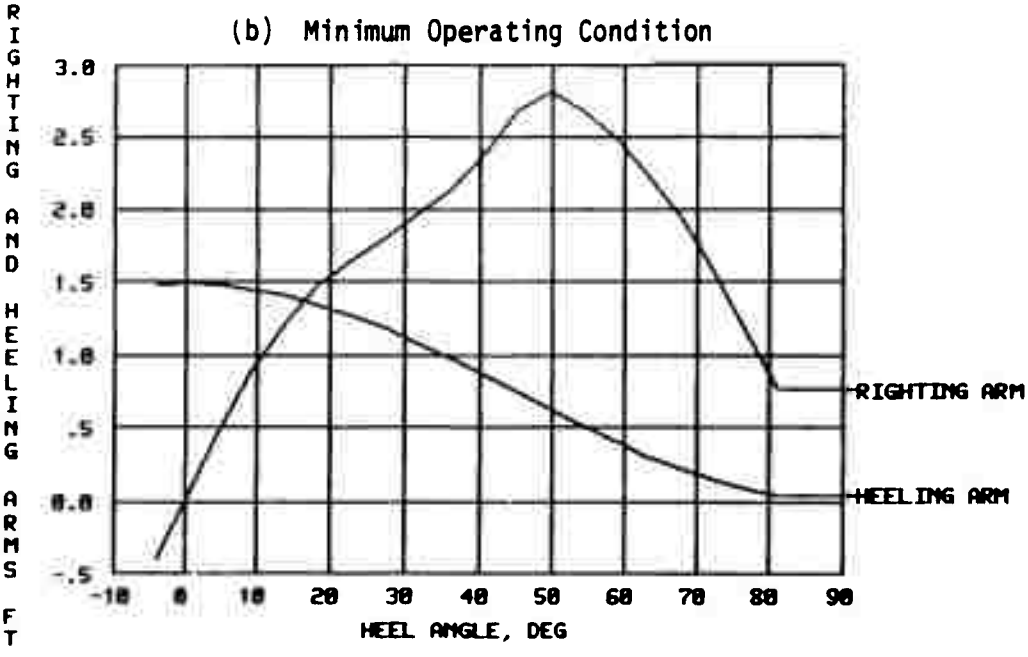
TABLE OF DAMAGED RIGHTING ARMS(RA), DRAFTS, AND TRIMS, FT

HEEL, DEG	DAMAGED COMPTS		-15.0	-5.0	0.0	5.0	10.0	15.0	20.0	25.0	35.0	45.0
RA	1	2	-1.36	-.50	0.00	.50	.97	1.36	1.66	1.88	2.25	2.80
TRIM	1	2	-1.68	-1.22	-1.13	-1.22	-1.41	-1.68	-1.98	-2.29	-2.82	-3.13
DRAFT	1	2	3.52	3.90	3.83	3.80	3.70	3.53	3.27	2.90	1.78	.03
RA	2	3	-1.19	-.42	0.00	.42	.83	1.19	1.50	1.79	2.22	2.42
TRIM	2	3	-7.09	-6.48	-6.40	-6.48	-6.70	-7.09	-7.57	-8.13	-9.48	-11.36
DRAFT	2	3	4.68	4.92	4.94	4.92	4.83	4.68	4.46	4.15	3.21	1.91
RA	3	4	-.90	-.33	0.00	.33	.62	.90	1.14	1.34	1.56	1.59
TRIM	3	4	-6.70	-6.40	-6.34	-6.40	-6.53	-6.71	-6.93	-7.22	-8.15	-9.74
DRAFT	3	4	6.25	6.43	6.45	6.43	6.36	6.25	6.07	5.82	5.11	4.12
RA	4	5	-.70	-.23	0.00	.23	.47	.70	.92	1.14	1.54	1.73
TRIM	4	5	.25	.14	.12	.14	.19	.25	.29	.30	.23	.06
DRAFT	4	5	5.51	5.64	5.65	5.64	5.59	5.51	5.36	5.14	4.41	3.33
RA	5	6	-.95	-.33	0.00	.33	.65	.95	1.26	1.52	2.02	2.28
TRIM	5	6	3.16	2.98	2.94	2.97	3.06	3.16	3.25	3.31	3.42	3.85
DRAFT	5	6	4.28	4.46	4.48	4.46	4.40	4.28	4.10	3.82	2.90	1.48
RA	6	7	-1.13	-.40	0.00	.40	.77	1.13	1.45	1.69	2.14	2.57
TRIM	6	7	2.49	2.44	2.44	2.44	2.46	2.49	2.47	2.37	2.00	2.00
DRAFT	6	7	3.66	3.88	3.91	3.88	3.80	3.66	3.44	3.12	2.08	.42



INTACT STATIC STABILITY - FIGURE 1 OF 2

DISPLACEMENT, LTON	136.90	LCG LOC(+VE FWD MID), FT	-2.6
KG, FT	7.38	WIND SPEED, KT	70.0
FOIL POS IND-DOWN			



INTACT STATIC STABILITY - FIGURE 1 OF 2

DISPLACEMENT, LTON	100.00	LCG LOC(+VE FWD MID), FT	-1.2
KG, FT	8.06	WIND SPEED, KT	70.0
FOIL POS IND-DOWN			

Figure 11 - WPB-H Intact Stability Characteristics

OPERATIONAL CHARACTERISTICS

RANGE AND ENDURANCE

Range and endurance versus speed characteristics of the WPB-H design are shown in Figures 12 and 13. Calculations were based on the one-half fuel load condition which takes fuel burnoff into account. Useable fuel is calculated at 98% of the fuel load, and 10% of this amount is considered for reserve for 27 L.tons available fuel.

Calculations resulted in a hullborne range at 12 knots of 3113 nautical miles (nm) which is comparable to 259 hours endurance. In the foilborne mode the range at 30 knots is 1165 nm or an endurance of 38.8 hours.

The mixed mode, 5-day mission operation for 96 hours at 12 knots and 24 hours at 30 knots requires a total of 25.7 L.tons of fuel. This is derived from fuel rates of 119.73 nm/ton and 44.8 nm/ton for the hullborne and foilborne conditions respectively. The fuel available, taking into account a 10% reserve, is greater than 25.7 L.tons by about 1.3 L.tons. At these speeds, total distance traveled is 1872 nm in five days.

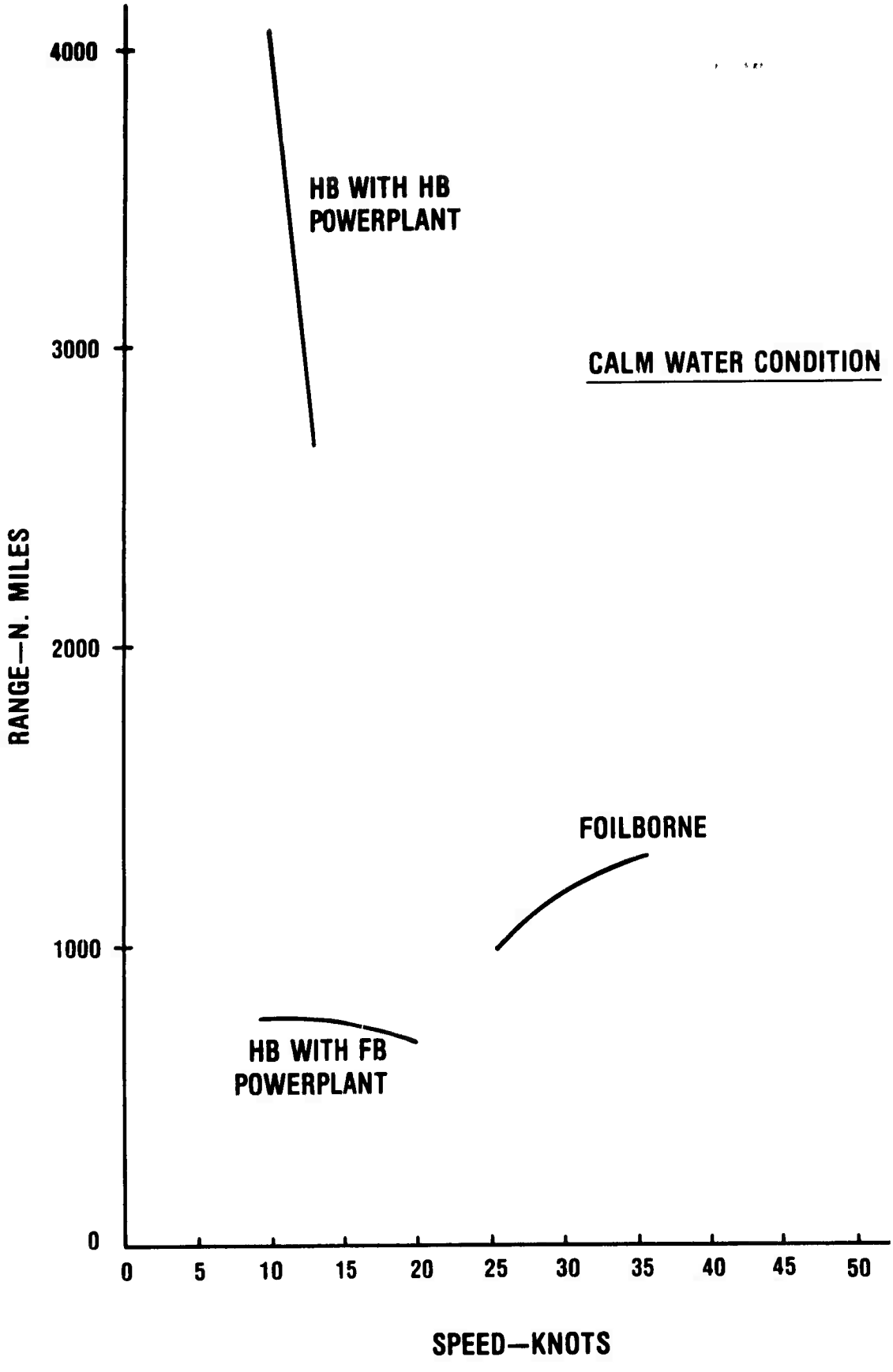


Figure 12 - WPB-H Range Characteristics

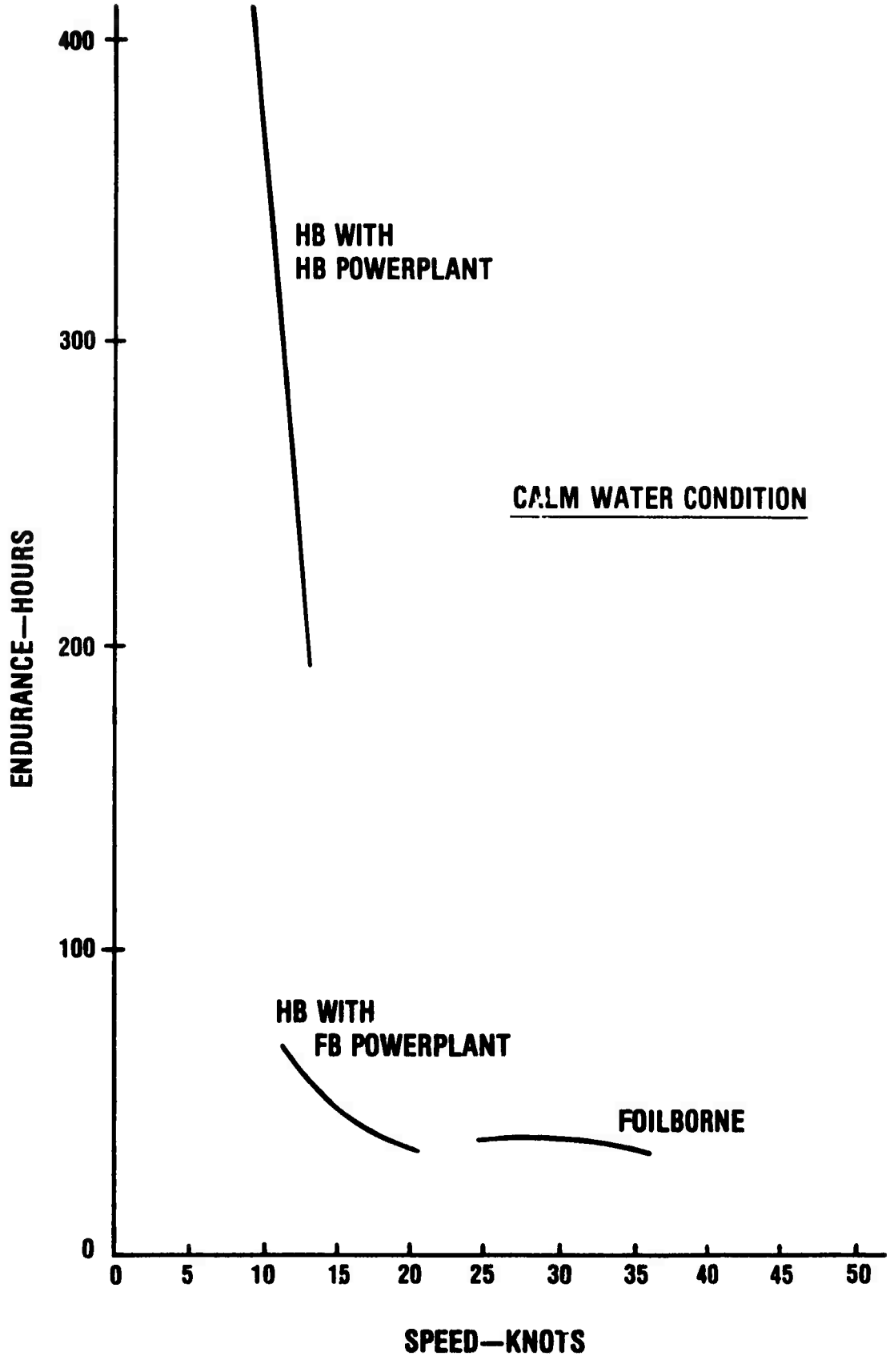


Figure 13 - WPB-H Endurance Characteristics

SPEED DEGRADATION

Although no rigorous analysis of speed degradation was made of this WPB-H design, Figure 14 presents the best estimate of this characteristic based on the HIGH POINT (PCH-1). This is justified since PCH-1 is a 125 L.ton hydrofoil with a similar fully submerged foil system configuration and a similar hull design.

Figure 14 shows that the maximum speed of the WPB-H will start to drop off at about mid Sea State 3 and reaches an estimated value of .90 Vmax at mid Sea State 5. Note that the trend follows that of the PCH-1 shown here for reference. If the WPB-H transmission were designed to accept the full power (4000 hp) of the LM-500 engine, it is estimated that the ship could maintain a speed up to 35 knots in Sea State 5. The maximum calm water speed of the WPB-H would then be about 38 knots with some increase in transmission weight of about 0.2 L. tons and comparable reduction in fuel load and range.

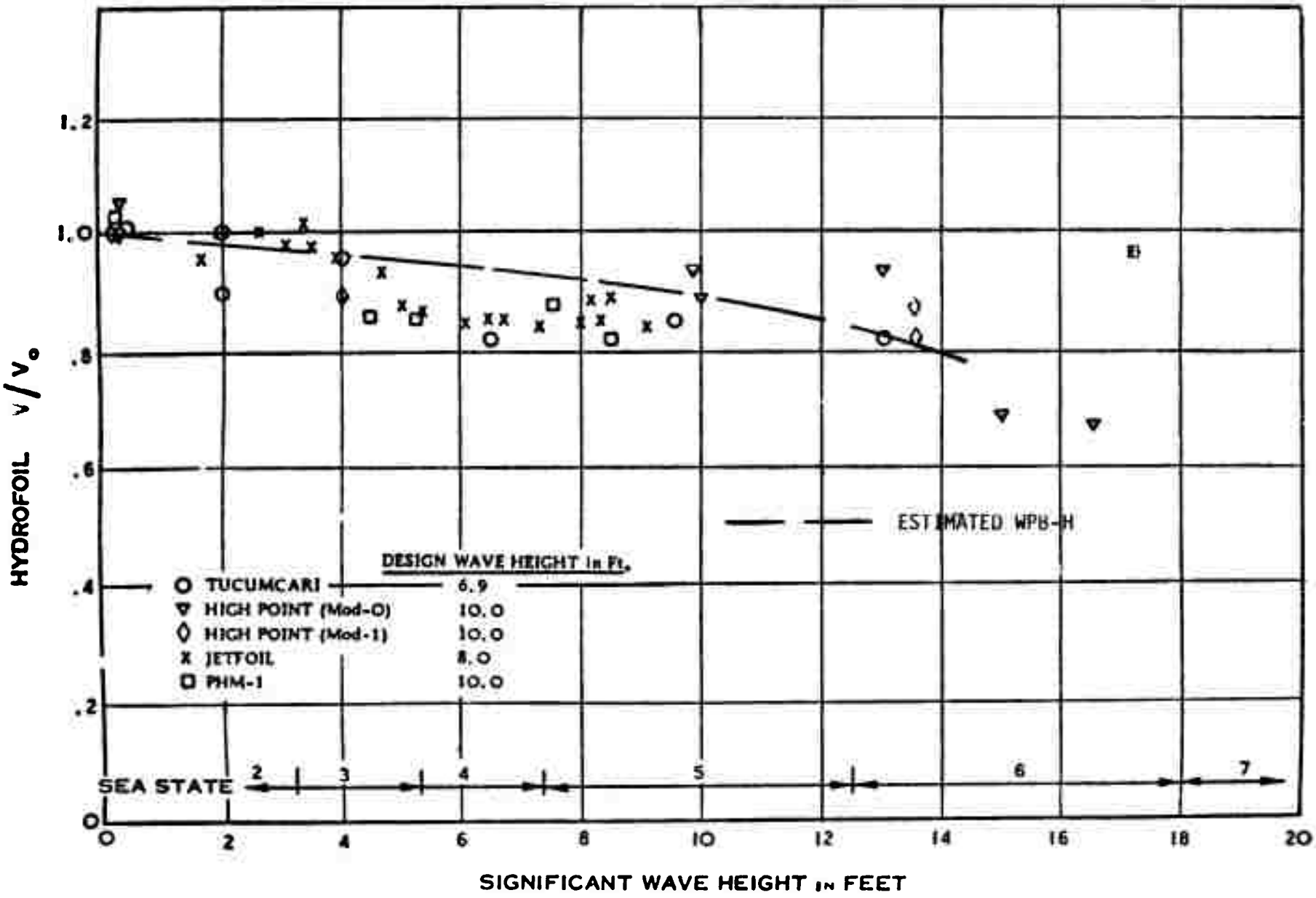


Figure 14 - Hydrofoil Speed Degradation

MOTIONS

Following the approach in the previous section on speed degradation, it is expected that motions in heave, pitch and roll will be comparable to those of HIGH POINT (PCH-1) hydrofoil. Motions for PCH-1 are shown in Figure 15. Note the relatively low values for pitch and roll which, of course, is derived from the excellent control afforded by a fully submerged foil system.

A plot of significant wave height against speed to show the operational boundaries of WPB-H as determined by power and vertical acceleration limits is shown in Figure 16. The U.S. Coast Guard requires that a 0.4g (significant single amplitude) vertical acceleration limit be shown. Since the WPB-H vertical accelerations are estimated to be much lower than this even in Sea State 5 and lower 6, a reference 0.2g limit line is shown. As can be seen therefore in Figure 16, the WPB-H should not be severely restrained by motions and accelerations up through Sea State 5.

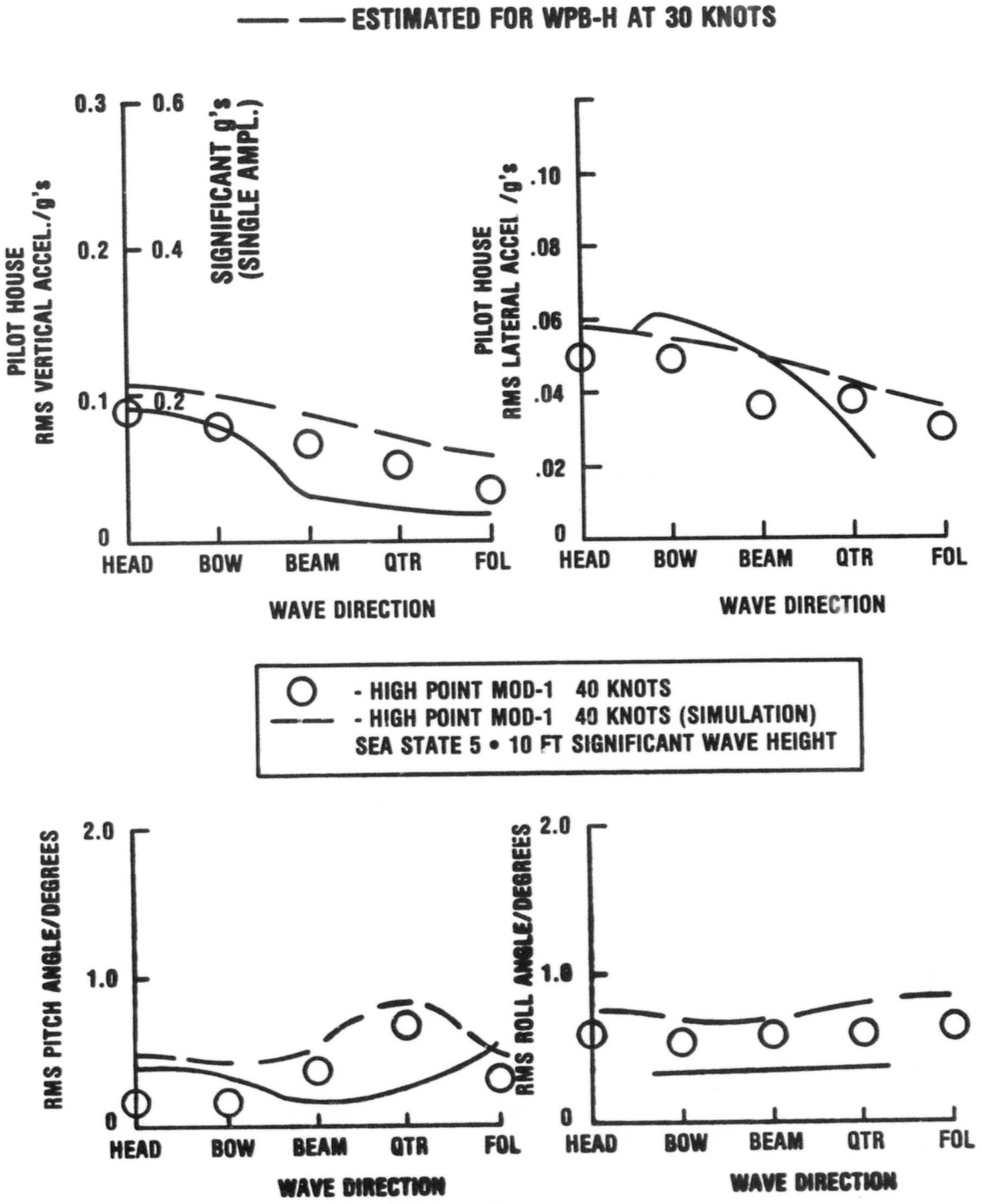


Figure 15 - WPB-H Estimated Motions

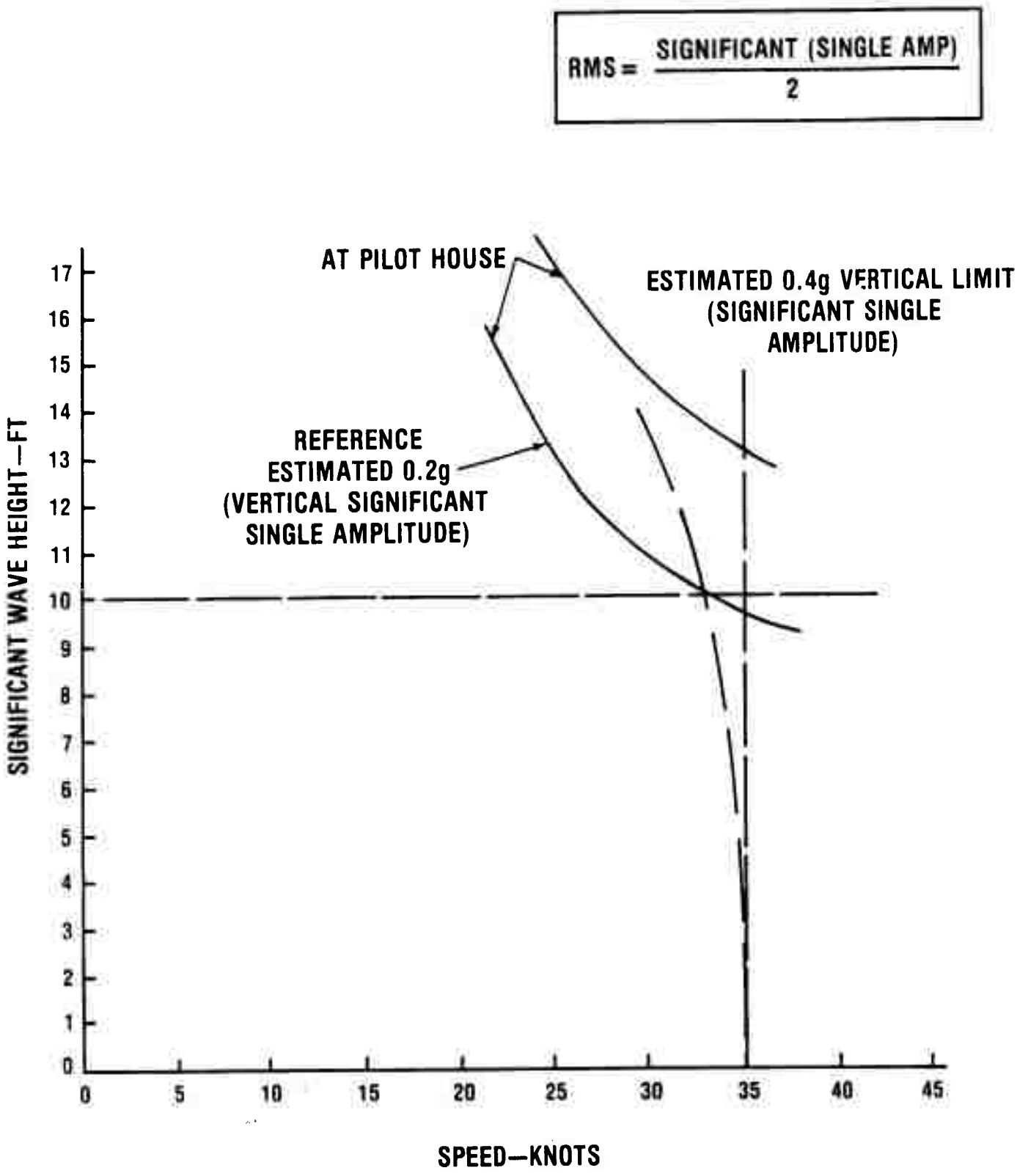


Figure 16 - WPB-H Vertical Acceleratio Operat ion Limit

TOWING

The WPB-H towing requirement is for a 500-ton disabled ship at 5 knots. The estimated power required for WPB-H at 5 knots with foils down is about 80 shp. Since the power available from the hullborne diesel is 650 shp, the power available for towing is 570 hp. This is equivalent to a thrust available of about 11,130 lbs at 5 knots assuming a propulsive efficiency of 30%. The drag of a 500-ton ship is estimated at about 5000 lbs at 5 knots. Therefore, the WPB-H has the towing capability (with foils down) required by more than a factor of two.

It is not recommended that towing be performed by the WPB-H with foils retracted. If this becomes a necessity, however, a raised tow point could be provided to avoid contact between the hawser and trailing edge of the raised aft foil.

BOAT LAUNCH AND RETRIEVAL

Boat launch and retrieval is essential to the WPB mission. This ship is provided with a 5.4m Rigid Hull Inflatable boat and a small telescoping crane located on the fantail. This arrangement permits the boat to be launched and recovered from either side.

Although this can be done with the foils either up or down, it is recommended that foils be down. With the foils down, the ship motions are expected to approach those of the foilborne case shown in Figure 15. The relatively high GM (5.3 ft at full load and 5.9 ft at the minimum operating condition) tends to reduce roll amplitudes but increase roll acceleration. However, the foils damp roll exceeding well. The result is low roll angles and low roll accelerations. The foils act in a similar manner to minimize pitch and heave.

Because the boat is launched and recovered in the way of the struts, the boat is provided with a good lee. This also improves the efficiency of the operation.

Foils should be raised when the ship is in shallow water. This eliminates the benefit of the foils. However, motions should be similar to those of a conventional WPB. Excitation should be reduced in shallow water.

The WPB-Hydrofoil should have excellent boat launch and retrieval capability.

VARIANTS

LOW SPEED

A low speed variant of WPB-H baseline ship was investigated. A design speed of 5 knots less than the baseline 35 knot speed was used as an input to HANDE. Since it was anticipated that less fuel would be required at a lower foilborne range speed and some weight savings may be realized in the propulsion system, dynamic lift of 125 L.tons and a shortened hull at 100 feet were selected for the design.

Because of the favorable specific fuel consumption of the LM-500 engine compared to other lower powered gas turbines, it was retained at a flat rating of about 2800 hp maximum continuous. The overall impact of the above changes is shown in Tables 8 and 9. Note that the 5-day mission requirement is satisfied with 96 hours at a hullborne speed of 12 knots and 24 hours at a foilborne speed of 27 knots for a total range of 1800 nm. The hullborne range is somewhat more than the baseline design at 3209 nm at 12 knots. This is primarily due to the greater amount of fuel available. However, foilborne range is only slightly less at 1126 nm, but at a speed of 27 knots rather than the baseline range speed of 30 knots. Fuel consumption at 27 and 30 knots foilborne is 218 gal/hr and 203 gal/hr, respectively.

HIGH SPEED

A 40-knot design speed variant of the baseline WPB-H was examined. It became evident that the LM-500 engine did not have sufficient power for 40 knots. A Detroit-Diesel Allison DDA-570 KA gas turbine was selected with a rating of 5270 hp maximum continuous. This was more than adequate for the high speed variant and provided a 64% take-off margin.

The hull dimensions were unchanged from the baseline design, however, foil loading was increased to 1100 psf for both forward and aft foils to improve high speed performance.

The overall impact of the above changes is shown in Tables 8 and 9. The 5-day mission requirement is satisfied with 96 hours at a hullborne speed of 12 knots and for 24 hours at a foilborne speed of 30 knots for a total range of 1872 nm. As in the low speed variant, hullborne range at 12 knots is greater at 3242 nm. Foilborne range of 1094 nm is only slightly less than the baseline design at the same 30-knot range speed. Fuel onsumption at 30 and 40 knots foilborne is 232 gal/hr and 332 gal/hr, respecti ely.

TABLE 8 - WPB HYDROFOIL PHYSICAL CHARACTERISTICS COMPARISON

SIZE:	WPB-H Low Speed Variant	WPB-H Baseline	WPB-H High Speed Variant
LOA	103 feet	108 feet	108 feet
LBP	100 feet	105 feet	105 feet
Hull Material	Welded Aluminum	Welded Aluminum	Welded Aluminum
Beam (at deck)	27.1 feet	28.4 feet	28.4 feet
Max Span (over foils)	37.5 feet	38.3 feet	36.4 feet
Draft (HB, Foils Down)	16.8 feet	16.8 feet	16.8 feet
Draft (HB, Foils Up)	4.4 feet	4.4 feet	4.4 feet
Depth	11.36 feet	11.93 feet	11.93 feet
Hull Volume	18,645 cubic feet	21,589 cubic feet	21,589 cubic feet
Deck House Volume	5,533 cubic feet	6,312 cubic feet	6,312 cubic feet
Total Volume	24,178 cubic feet	27,901 cubic feet	27,901 cubic feet
Lightship Weight	87.2 L.tons	95.0 L.tons	93.3 L.tons
Full Load Weight	131.3 L.tons	137.0 L.tons	135.8 L.tons
SPEED:			
Foilborne Design	30 knots	35 knots	40 knots
Take-off	22 knots	22 knots	23.5 knots
Hullborne Design	12 knots	12 knots	12 knots
RANGE:			
Foilborne	1,126 nm at 27 knots	1,165 nm at 30 knots	1,094 nm at 30 knots
Hullborne	3,209 nm at 12 knots	3,113 nm at 12 knots	3,242 nm at 12 knots
ENDURANCE:			
Five-Day Mission	12 knots for 96 hours, and 27 knots for 24 hours, for total of 120 hours and 1,800 nm	12 knots for 96 hours, and 30 knots for 24 hours, for total of 120 hours and 1,872 nm	12 knots for 96 hours, and 30 knots for 24 hours, for total of 120 hours and 1,872 nm
PROPULSION:			
Foilborne	(1) LM-500; (2) Zee-drives	(1) LM-500; (2) Zee-drives	(1) DDA-570 KA; (2) Zee-drives
Hullborne	(1) Detroit Diesel 12V-71TI(L)	(1) Detroit Diesel 12V-71TI(L)	(1) Detroit Diesel 12V-71TI(L)
Electric Prime Mover	Diesel, 280 kw	Diesel, 280 kw	Diesel, 280 Kw
Foilborne HP required (cruise)	2,800 hp at 27 knots	2,920 hp at 30 knots	3,010 hp at 30 knots
Foilborne HP required (max cont.)	2,756 hp at 30 knots	3,500 hp at 35 knots	4,252 hp at 40 knots
Take-off HP required	3,148 hp	3,784 hp	3,744 hp
Take-off Margin	1.51	1.30	1.64
Hullborne HP required	668 hp at 12 knots	627 hp at 12 knots	627 hp at 12 knots
FOILS:			
Foil Concept	Canard (T/Pi)	Canard (T/Pi)	Canard (T/Pi)
Strut/Foil Material	Struts: HY-130 Foils: HY-130	Struts: HY-130 Foils: HY-130	Struts: HY-130 Foils: HY-130

TABLE 9 - WPB HYDROFOIL WEIGHT BREAKDOWN COMPARISON

SWBS	Group	Low Speed Variant Weight (L.tons)		Baseline Weight (L.tons)		High Speed Variant Weight (L.tons)	
100	Hull Structure		25.4		28.4		28.4
200	Propulsion Plant		11.9		12.5		11.9
	FB Components	5.4		6.0		5.4	
	HB Components	6.5		6.5		6.5	
300	Electric Plant		9.9		10.6		10.4
400	Command & Surveillance		2.0		2.0		2.0
500	Auxiliary Systems		20.5		22.1		21.3
	Systems (less 567)	11.2		12.2		12.2	
	F/S Assemblies	9.3		9.9		9.1	
600	Outfit & Furnishings		9.0		10.4		10.4
700	Armament		2.5		2.5		2.5
M00	Margins (10%)		8.2		8.7		8.6
	LIGHTSHIP		89.4		97.2		95.5
F00	Full Loads		41.9		39.8		40.3
F10	Crew & Effects	3.0		3.0		3.0	
F30	Provisions	2.5		2.5		2.5	
F42	Fuel (98% usable)	31.6		29.5		30.0	
F46	Lube Oil	0.3		0.3		0.3	
F50	Fresh Water	4.5		4.5		4.5	
	FULL LOAD WT-FOILS DOWN		131.3		137.0		135.8
	FB Foil/Strut Buoyancy		-6.3		-7.0		-5.8
	FULL LOAD DYNAMIC LIFT		125.0		130.0		130.0

It should be noted from Table 9 that the foilborne propulsion components weight for the high speed variant is less than the baseline design value. This is attributed in part, to the lower torque requirements of the propulsion train since the output speed of the DDA-570 KA engine is 11,500 rpm compared to 7,000 rpm of the LM-500. Also the lighter weight of the 570 KA engine (1350 lbs) compared to the LM-500 (2000 lbs) contributes to this characteristic. The strut/foil system weight of the high-speed variant is also less than that of the baseline. The higher foil loading of the high-speed variant results in smaller foils (for the same lift) than those on the baseline. The smaller foils, in turn, weigh less.

CONCLUSIONS

The following conclusions can be drawn from the foregoing work:

1. The baseline WPB-H with a 35-knot design speed and full load weight of 137 .tons satisfies all of the U.S. Coast Guard WPB requirements. The foilborne propulsion system consists of a LM-500 gas turbine driving into a splitter gear box to divide the power between two vertical shafts in the aft struts. One fixed pitch propeller 3.7 ft in diameter (44 inches) is mounted on the propulsion pod at the bottom of each aft strut. The hullborne plant is a Detroit Diesel 12 V-71TI(L) powering a retractable stern drive with a fixed pitch propeller.

2. The WPB-H has sufficient fuel with a 10% reserve to operate for 96 hours at 12 knots and 24 hours at 30 knots for a total distance travelled of 1872 nautical miles.

3. A high speed variant of the WPB-H baseline design was investigated at a 40-knot design speed. It was designed to meet all of the USCG WPB requirements. The higher speed required a Detroit Diesel Allison 570 KA gas turbine flat rated at about 4300 hp. The higher speed variant provides a 5-knot greater speed than the baseline with no technical penalties.

4. A low speed variant of the WPB-H baseline design was investigated at a 30-knot design speed. This variant also met all of the USCG WPB requirements. The LM-500 gas turbine engine was retained for foilborne propulsion.

The 5-knot reduction in design speed does not appear to lead to any significant advantages over the 35 and 40 knot WPB-H designs. This is due principally to the typical fully submerged hydrofoil power characteristic in the speed range of 30 to 35 knots where power required is not strongly dependent upon speed.

REFERENCES

1. King, James H., "Hydrofoil Concepts For United States Coast Guard Missions," DTNSRDC Report No. DTNSRDC/SDD-84/2 (January 1984).

2. King, James H. and Devine, M. D., "HANDE - A Computer-Aided Design Approach for Hydrofoil Ships," Naval Engineers Journal, April 1981.